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EVAPORATION IN THE LONDON AREA FROM 1698 TO 1970

By B. G. WALES-SMITH

Summary. The preparation from the available data (limited in early years) of monthly estimates of (Penman) potential evaporation representative of Kew for the period from 1698 to 1970 is described and illustrated. Measurements made with British Standard evaporation tanks at Camden Square (1885–1955) and Kew Observatory (1949–70) are examined and a simple method of adjusting either record to extend the other (approximately) is proposed.

Introduction. A series of monthly and annual totals of rainfall representative of Kew (1697–1970) has already been assembled and analysed (Wales-Smith[1,2]). Evaporation, the other component of the atmospheric phase of the water cycle, is equally important in studies of water resources, agriculture, drainage and flood control.

Data required for the calculation of estimates of potential evaporation (PE) by Penman's formula.[3] This well-known and widely tested formula makes use of basic climatological data. The variables of which time-averages are required are air temperature and vapour pressure (in the screen), daily duration of bright sunshine and run-of-wind at 2 metres above ground.

Data available.

(a) Temperature: for 1698–1811 monthly estimates based on a variety of records; and for 1812–1970 averages of routine measurements, at Greenwich and at Kew.

(b) Vapour pressure: for 1876–1970 averages obtained from routine hygrometric readings taken at Kew.

(c) Duration of bright sunshine: for 1876–1970 averages of routine measurements at Kew.

(d) Run-of-wind: for 1870–1970, averages of routine anemometer readings (20–23 metres above ground); and for 1957–70, averages of daily readings from an anemometer 2 metres above ground, all at Kew.

Possible length of a series of potential evaporation (PE) estimates. By estimating 2-m wind speeds from 20–23-m speeds it was, clearly, possible to apply Penman's formula, as used in the Meteorological Office (Grindley[4]) to data from 1876 (October) onwards.

The remaining question was to find out if useful monthly estimates of PE could be made with temperature data only. The first step was to plot monthly diagrams of air temperature against PE for the decade 1961–70 (Figure 1). The relationships leave much to be desired, but, as shown by the lines (fitted by eye) the project is not by any means hopeless.

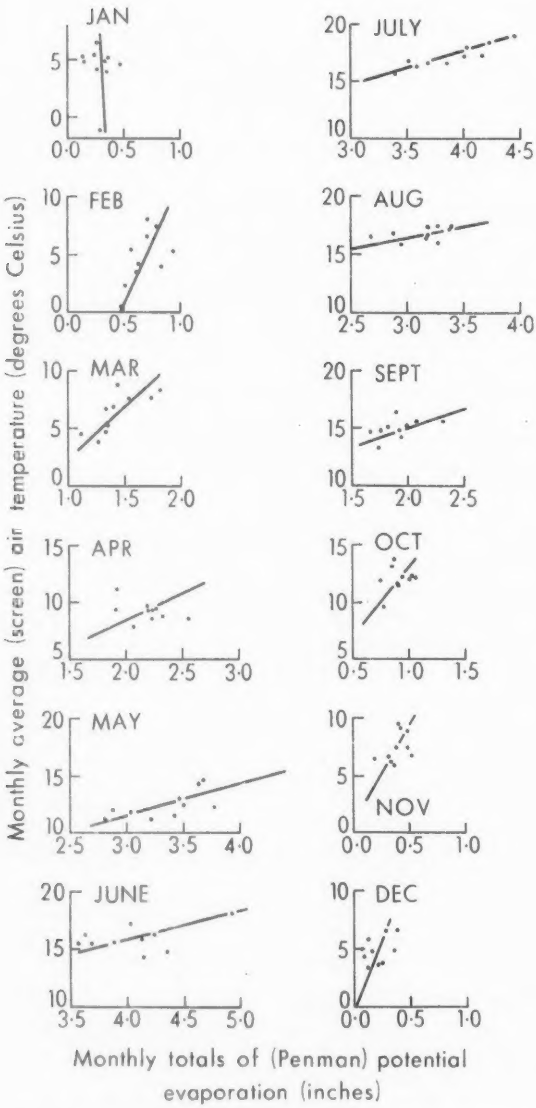

FIGURE 1—MONTHLY AVERAGE (SCREEN) AIR TEMPERATURE AND MONTHLY TOTALS OF (PENMAN) POTENTIAL EVAPORATION (ALBEDO 0·25) AT KEW 1961–70

The next step was to look at relationships between monthly averages of air temperature and vapour pressure and between air temperature and duration of bright sunshine and to see how well long-period average monthly wind speeds approximated to actual monthly averages. These steps were designed to provide means of obtaining estimates to replace missing data and also to approach the problem from a physical point of view.

Monthly averages of air temperature and daily duration of bright sunshine. It is well known that many of the mildest winter days are overcast and that some of the sunniest days in any season are by no means the warmest. The relationship between averages of temperature and sunshine duration would be expected to be poor in winter and not entirely satisfactory at other times of the year. Monthly scatter diagrams of average air temperature against average daily duration of bright sunshine for the period 1921–40, at Kew, are shown as Figure 2.

The winter relationships are poor; those for other months are better but there is a wide scatter of sunshine values for any given temperature. Plausible curves were drawn by eye and then the 1931–60 averages of temperature and sunshine were plotted (as crosses).

Three methods were used to estimate monthly averages of daily duration of bright sunshine at Kew for the decade 1961–70.

(a) Estimates were obtained from temperatures by means of the curves in Figure 2.
(b) The 1931–60 sunshine averages were used as estimates.
(c) The 1931–60 sunshine averages were used from November to February and the temperature-derived estimates, (a), were meaned with the 1931–60 sunshine averages for the other months.

The distributions of errors arising in these three methods were examined. The use of 1931–60 sunshine averages gave fewer large differences from the 1961–70 values than did the use of temperature-derived estimates. The combined method compared favourably with the use of averages and has the advantage of taking into account the radiation–temperature relationship characteristic of the warmer months of the year.

Monthly averages of air temperature and vapour pressure. Monthly temperature averages and averages of vapour pressure (computed from daily mean temperature and daily mean relative humidity) for Kew were plotted against one another for the period 1921–40. Plausible lines of best fit were easily inserted by eye, the month-to-month trend of the slope being used as an aid to positioning the lines for summer months. The relationships are good or very good.

Run-of-wind at 2 metres above ground level. The distribution of monthly averages of 2-m run-of-wind at Kew for the period 1957–70 was tabulated against average to show the greatest errors which resulted from using the 1957–70 monthly averages as estimates of actual monthly averages over 14 years. The errors, never exceeding 1·9 knots, or 53 miles run-of-wind (per day) are acceptably small for the present purpose.

Comparison of Penman PE estimates made with limited and full data. Monthly PE estimates were calculated (using a computer program designed by A. G. Seaton) for the decade 1961–70 at Kew by using real

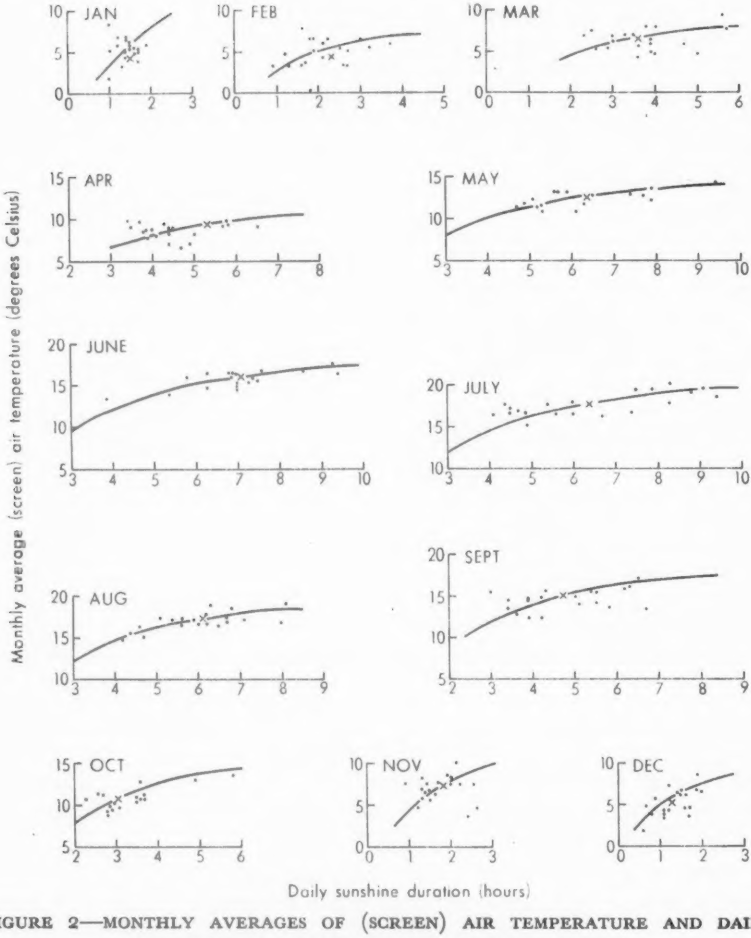

FIGURE 2—MONTHLY AVERAGES OF (SCREEN) AIR TEMPERATURE AND DAILY DURATION OF BRIGHT SUNSHINE AT KEW 1921–40

X averages for period 1931–60

temperature data, estimated duration of sunshine (from temperatures and sunshine averages), estimated vapour pressure (from temperature) and 1957–70 monthly average values of run-of-wind at 2 metres above ground level.

Monthly estimates had also been calculated, for the same decade, using real data. The two sets of 120 estimates were compared; the estimates based on limited data were almost always within ½ inch (12·7 mm) of those based on full data.

Tables to permit PE to be estimated from temperature. Comparison of the two sets of estimates showed that those based on limited data were generally lower than the corresponding full data estimates from October

to March. Monthly scatter diagrams of air temperature against limited data PE were drawn and lines of best fit inserted by eye (Figure 3). Monthly tables were produced from Figure 3 but the values for the colder months were multiplied by empirical adjusting factors as follows :

Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
1·069	1·653	1·351	1·490	1·335	1·099

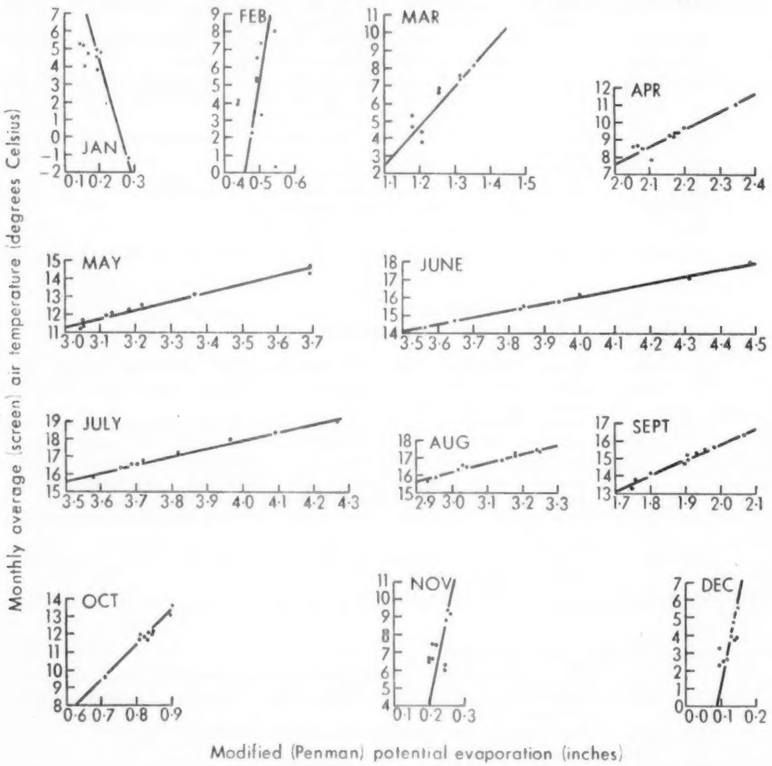

FIGURE 3—MONTHLY RELATIONSHIPS BETWEEN AVERAGE SCREEN TEMPERATURE AND MODIFIED (PENMAN) POTENTIAL EVAPORATION AT KEW 1961–70

Comparison of PE estimates obtained from the tables with those obtained from Figure 1. Although it has been shown that missing data can be quite well estimated using the above methods and that useful monthly PE estimates can be obtained from average temperatures, it remains to be shown that the method is as good as a direct regression of temperature against known PE. Estimates of PE were read from the lines on Figure 1. These estimates and those obtained by using the tables (Figure 3 values with winter half-year adjustments) were compared with the corresponding PE estimates obtained from full data for 1961–70 for Kew. The distribution of errors was examined. It was found that the estimates from the tables were somewhat better than those obtained from Figure 1 (bearing in mind that the lines in Figure 1 are not calculated regression lines).

Sources and adjustment of data. Sources and methods of processing data are given below for those readers who wish to examine them.

(a) Monthly average (screen) air temperature at Kew Observatory.

Sources of data and estimates.

1698–1722	Manley's[5] Central England series adjusted to give estimates for the London Region by a regression obtained over the period 1723–32.
1723–1811	Manley, G.; Temperatures for the London Region. (Typescript communicated to the Meteorological Office 1967).
1812–Oct. 1822	Greenwich Observatory values (Eaton[6]) adjusted to give estimates for Kew by regression, over the period 1871–80.
Nov. 1822–1840	Various sites in the Greenwich area. Values adjusted by subtracting 0·2 degC (to 'correct' from 25–40 ft to observatory height, 155 ft) then adjusted as for 1812–22 (Eaton[6]).
1841–70	Greenwich Observatory temperatures adjusted as for 1812–40 (Brazell[7]).
1871–1920	Kew Observatory Temperatures (Brazell[7]).
1921	*Meteorological and Magnetic Year Book* Kew temperatures.
1922–56	*Observatories Year Books* Kew temperatures.
1957–70	*Monthly Weather Reports* Kew temperatures.

(b) Monthly averages of vapour pressure (in the screen) at Kew Observatory.

Sources of data and estimates.

1870–Sept. 1876	Estimated from air temperatures.
Oct. 1876–1910	*Reports of the Kew Observatory Committee of the Royal Society* and *Reports of the National Physical Laboratory and Observatory Department* (Meteorological Office Library).
1911–21	*British Meteorological and Magnetic Year Books* (Meteorological Office Library). Values for 1911–1913 were obtained from average temperature and average relative humidity. Values for 1914–20 are means of vapour pressures at 09 and 21 GMT. Values for 1921 were computed from daily mean temperature and daily mean relative humidity.
1922–56	*Observatories Year Books* (Meteorological Office Library), computed as for 1921.
1957–70	*Monthly Weather Reports* of the Meteorological Office. Averages of values at 09, 15 and 21 GMT.

(c) Monthly averages of daily duration of bright sunshine at Kew Observatory.

Sources of data and estimates.

1870–Sept. 1876	Estimated from air temperature and long-period monthly averages of sunshine duration. (Jan., Feb., Nov. and Dec. 1931–60 sunshine averages used).
Oct. 1876–1880	*Reports of the Kew Observatory Committee of the Royal Society.*
1881–1920	Brazell.[7]
1921	*British Meteorological and Magnetic Year Book.*
1922–56	*Observatories Year Books.*
1957–70	*Monthly Weather Reports.*

(d) Monthly averages of run-of-wind at 2 metres above ground at Kew Observatory.

Estimates are based on the measured values at 20–23 metres above ground from 1870 to 1956.

Sources of data.

1870–Sept. 1876	Wind tabulations for Kew 1868–77 (Meteorological Office Archives).
Oct. 1876–1910	*Reports of the Kew Observatory Committee of the Royal Society* and *Reports of the National Physical Laboratory and Observatory Department* (Meteorological Office Library).
1911–21	*British Meteorological and Magnetic Year Books* (Meteorological Office Library).
1922–56	*Observatories Year Books* (Meteorological Office Library).

The values from 1957 onwards are measured run-of-wind at 2 metres.

Notes :

(1) Data from 1870–1925 are from the Robinson anemometer, variously stated to have been at 70 ft (21·3 m) and 20 m above ground.

(2) Values for 1870–1905 have been multiplied by 2·2/3 to remove the inconsistency introduced by the change of instrumental multiplying factor.

(3) Data from 1926–1970 are from the Dines pressure-tube anemograph with head at 23 m above ground.

The annual averages of measured winds at 20–23 m were plotted. There had been an apparent, sustained increase from the beginning of the record to about 1930.

Decadal averages are as follows :

1871–80	1881–90	1891–1900	1901–10	1911–20	1921–30	1931–40	1941–50	1951–60	1961–70	
180	178	180	187	188	188	205	200	202	206	miles/day

From this simple table it is easy to derive factors to remove most of the slope from the graph.

For 1871–1900, multiply by 203/180 or 1·128.

For 1901–30, multiply by 203/188 or 1·080,

it being assumed that the increase has been mostly due to greater sensitivity of measuring and recording apparatus over the years.

Thus, starting with the raw, published data the following modifications have been made to produce estimates of 2-metre wind-run (monthly average daily run). 1870–1905 adjusted for instrument factor change. 1870–1930 adjusted for apparent low sensitivity of wind-speed measurements. 1870–1956 values adjusted to give estimates of 2-metre speeds.

The factor to adjust from 23 to 2 metres (0·54) was obtained by plotting monthly averages of measured run-of-wind at 2 metres above ground against average wind speed at 23 metres (converted to run-of-wind) for the period 1957–70. (The points on the graph were all close to a straight line through the origin, where $V_2 = V_{23} = 0$).

Calculation of PE estimates. Estimates for 1698 to 1869 have been obtained from tables based on Figure 3 (with factors applied).

Estimates for 1870 to September 1876 have been obtained by using partly real and partly estimated data.

Estimates for October 1876–1970 have been obtained by using real data.

When seasonal (Nov.–Feb., Mar.–Apr., May–Aug. and Sept.–Oct.) yearly and decadal averages were examined it was found that there was a marked downward 'step' in the 'winter' graph after the decade 1861–70; estimates prior to 1870 were based on temperatures only. Comparisons of long-period averages give the following results :

	1700–1869	(1770–1869) *values in inches*	1870–1969
Winter	1·51	1·51	1·25
	1701–1870	(1771–1870)	1871–1970
Spring	3·45	3·45	3·43
Summer	13·91	13·87	14·10
Autumn	2·61	2·59	2·67

Adjustment was made by subtracting 0·25 in from all winter totals up to 1869 and adding 0·20 in to summer totals and 0·05 in to autumn totals. Monthly adjustments (in inches) were based on long-period average monthly percentages of annual potential evaporation totals as follows : Jan. −0·05,

Feb. −0·11, Mar. 0, Apr. 0, May +0·05, June +0·06, July +0·05, Aug. +0·04, Sept. +0·03, Oct. +0·02, Nov. −0·06, Dec. −0·03.

The period 1870–Sept. 1876 had to be treated differently, since real wind as well as temperature data had been used, sunshine and vapour pressure, however, being estimated.

Tank evaporation measurements, 1885 to 1970. Daily measurements of evaporative water loss from a British Standard evaporation tank (6 ft square and 2 ft deep) buried in grass-covered soil with the tank rim 3 inches above ground level have been made at Kew Observatory since 1 January 1949. Daily measurements from a similar tank, (also buried) were made from 1 January 1885 to 31 December 1955 at Camden Square, London.

The early measurements were made by G. J. Symons and later by H. R. Mill, for the British Rainfall Organization, and from 1922 the measurements were made by observers appointed by the Royal Meteorological Society.

The idea of making use of the historic Camden Square record and of the more recent and contemporary Kew record and (possibly) of combining them is attractive. The resulting 86-year record of evaporation from the 6-ft square surface of a 2-ft deep body of fresh water would provide not only a record of actual evaporation but also the data for various analyses of hydrometeorological interest.

The Camden Square record. Data for the more recent years of the record have long been regarded with suspicion and have been the subject of a good deal of expert scrutiny and discussion. Penman estimates of PE have been calculated, for Kew (using all the required data) from 1876 onwards. Figure 4 shows annual and seasonal comparisons between Kew PE and Camden Square tank evaporation. The lines of best fit have been inserted by eye, ignoring points representing annual and summer values for 1943 and later years (shown as crosses in the summer and annual diagrams) and the dated points in spring and autumn which, clearly, are not comparable with values for all other years.

Comparison between the Kew Penman PE series and the Camden Square tank record also suggested that the September tank total in 1906 and the April to August tank totals for 1903 were too large (1903 was the wettest known summer at Kew up to 1970) and adjustments have been made from the lines of best fit (inserted by eye) in month-by-month (scatter diagram) comparisons between Kew PE and Camden Square tank evaporation from 1885 to 1942 (inclusive).

From these monthly 'best-fit' lines and the series of PE estimates for Kew, approximate estimates of Camden Square tank evaporation were obtained for the period 1943–70. These estimates for Camden Square were compared with the Kew tank record from 1949 to 1970 in another set of monthly scatter diagrams. The lines run through the 22-year average values and the origin. The slope of each line has been expressed in terms of empirical factors to adjust either tank record to give an estimate of the other.

Comparison of Penman PE and tank evaporation at Kew. Monthly totals for the period 1949–70 were plotted on scatter diagrams and positions of the lines of best fit were estimated by eye. Points lying well away from these lines were identified and, after the climatological data used in the Penman calculations had been re-checked, these tank estimates were adjusted by half the distance to the line of best fit.

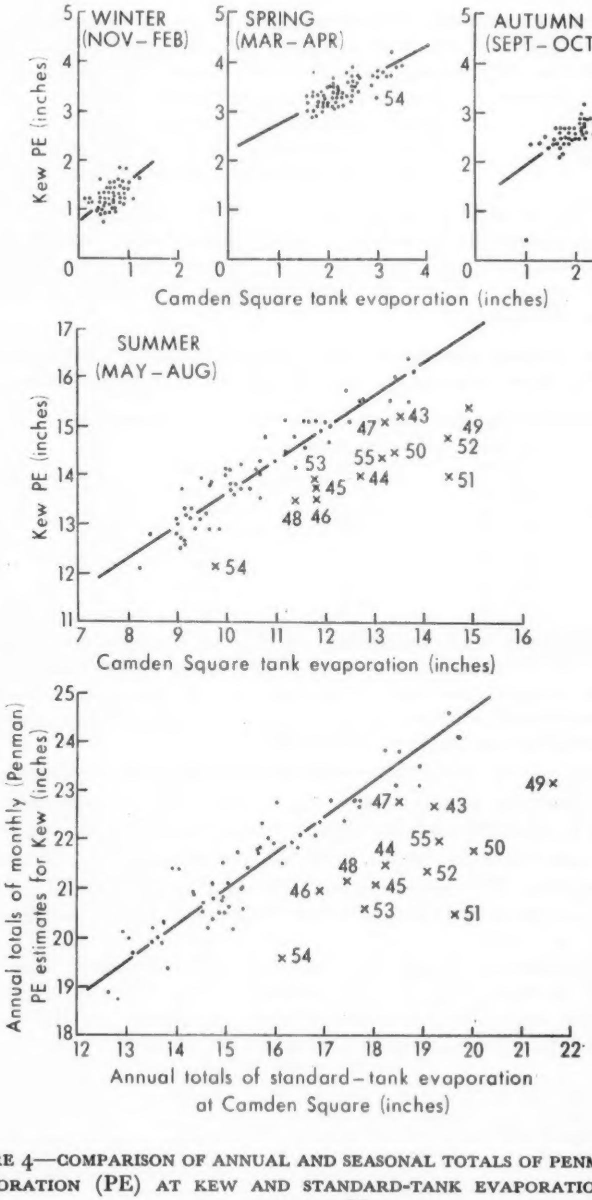

FIGURE 4—COMPARISON OF ANNUAL AND SEASONAL TOTALS OF PENMAN POTENTIAL EVAPORATION (PE) AT KEW AND STANDARD-TANK EVAPORATION AT CAMDEN SQUARE, 1885–1955

Numbers adjacent to plotted points indicate years of observation.

The 1:1 line was inserted on each diagram and it was of great interest to note the following monthly relationships between tank evaporation totals and Penman estimates (made with sunshine data and an albedo value of 0·25) which held on a high proportion of occasions over the 22-year period :

September to January	Tank evaporation $\geqslant$ Penman PE
February	Tank evaporation $\leqslant$ Penman PE
March to August	Tank evaporation $\leqslant$ Penman PE for small totals
	Tank evaporation $>$ Penman PE for large totals.

Records. The series of monthly estimates of PE representative of Kew was originally submitted as Appendix I; the Camden Square and Kew tank series were submitted as Appendices II and III. To save space these appendices have had to be omitted, but copies of the typescript sheets may be obtained from the Editor on request.

35-year and 10-year averages. The averages listed in Tables I and II are provided for direct comparison with Tables III and IV of Reference 1.

TABLE I—35-YEAR AVERAGE POTENTIAL EVAPORATION

35-year period	Representative values for Kew *inches*	*millimetres*
1706–40	21·71	551·4
1741–75	21·57	547·9
1776–1810	21·78	553·2
1811–45	20·72	526·3
1846–80	21·50	546·1
1881–1915	21·49	545·9
1916–50	21·39	543·3

Probable accuracy and sensitivity of PE estimates based on air temperature. It has been shown that the PE estimates are good when based on good-quality temperature data. The accuracy of the early estimates in the series depends upon the quality of the Manley temperature series and these are certainly the best estimates available.

The sensitivity of the temperature-derived estimates was investigated by two methods. First the monthly value of $\pm\ (M - \overline{M})$ was calculated for real Penman PE estimates and for temperature-derived PE for the decade 1961–70. (M = monthly PE total : $\overline{M}$ = 10-year average PE). Frequency diagrams of $\pm\ (M - \overline{M})$ were prepared. The temperature-derived estimates are, as would be expected, less sensitive to evaporative conditions than real Penman PE.

Next decadal extreme annual and 'summer' (May–August) totals were compared with corresponding decadal averages. The averages of extreme value differences from decadal average were calculated for the periods 1701–1870 and 1871–1970. Comparing the averages we have

			1701–1870	1871–1970
Whole year	Average decadal	max. minus average	1·37 in	1·93 in
	differences	average minus min.	1·22 in	1·87 in
'Summer'	Average decadal	max. minus average	1·22 in	1·65 in
	differences	average minus min.	0·99 in	1·55 in

Thus the ratios expressed as fractions

	(Max.)	(Min.)
Whole year	1·93/1·37 = 1·41	1·87/1·22 = 1·53
'Summer'	1·65/1·22 = 1·35	1·55/0·99 = 1·57

TABLE II—10-YEAR AVERAGES OF POTENTIAL AND TANK EVAPORATION IN INCHES

Decades	Kew PE	Kew tank	Camden Square tank
1701–10	21·35		
1711–20	21·23		
1721–30	21·79		
1731–40	22·04		
1741–50	21·70		
1751–60	21·55		
1761–70	21·33		
1771–80	22·24		
1781–90	21·58		
1791–1800	21·61		
1801–10	21·74		
1811–20	20·38		
1821–30	20·85		
1831–40	20·51		
1841–50	21·84		
1851–60	21·56		
1861–70	21·95		
1871–80	20·68		
1881–90	20·91		
1891–1900	21·95		15·66
1901–10	21·53		15·85
1911–20	21·11		15·21
1921–30	21·24		15·33
1931–40	21·53		15·78
1941–50	21·79		16·28 (estimated)
1951–60	21·87	23·26	16·38 (estimated)
1961–70	22·39	22·31	16·94 (estimated)
Mean of 27 decades	21·49		

give factors which could be applied to extreme values in early decades to give an approximation to the probable real maximum departures, positive or negative, from decadal averages.

Future plans. The series of evaporation estimates will be analysed along the lines of Reference 2 and in conjunction with the rainfall series (Reference 1).

Acknowledgements. The writer wishes to thank Mr M. J. Weller and Mr T. E. Oliver for valuable help in the search for early records, Mr W. H. Douglas of Kew Observatory for providing various essential data, and the data-punching staff of the Data Processing Branch of the Meteorological Office for punching and processing over 100 station-years of data. Mr A. Bleasdale and Mr J. Harding kindly read drafts of the paper and gave helpful comments and encouragement. (The paper on which this article is based is held in the National Meteorological Library, Bracknell, Berkshire.)

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AN OBJECTIVE METHOD OF CALCULATING AREAL RAINFALL

By E. J. ENGLISH

Summary. A model is described for the computer-based computation of rain amounts at points of a regular grid from a scattered distribution of rain-gauge values, for the purpose of estimating rainfalls over areas such as river sub-catchments. Some results are presented where computed areal rainfalls are compared with hand estimates.

Introduction. Several hundred estimates of sub-catchment areal rainfall using a gauge network were required in the Dee Weather Radar Project,[1] so it was necessary to develop a reliable computer-based objective method. It had to be flexible enough to accept any combination of the gauges, after one or more had been rejected by quality control procedures, to obtain estimates over areas whose shapes were dictated by river catchments.

Many models have been developed to obtain areal rainfall including a number which rely on weighting factors being applied to the observations, such as the well-known Thiessen's Method; a method based upon producing the weights by surface fitting;[2] and triangulation.[3] These methods require the weighting factors to be changed if one or more gauges in a network do not have valid data, which makes them unattractive for computer application, although Diskin[4] describes a method based on a Monte Carlo procedure for the production of Thiessen's Coefficients using a digital computer.

Inverse distance weighting has been used extensively for interpolation prior to forming areal rainfall, for example by Salter[5] in the Meteorological Office. This method has the drawback that no allowance is made for the position of the gauges relative to the interpolation point, also it cannot produce values at a point which are higher than the maximum or lower than the minimum gauge measurement. To overcome these difficulties surface fitting techniques[6,7] have been developed which attempt to describe the rainfall field as if it were a continuous pattern, much as an analyst does when drawing isohyets by hand.

The model chosen for use here is a combination of inverse distance-squared weighting and the fitting of a linear surface so that the main advantage of each is retained — namely the dominance of observations which are spatially close to the interpolation point and a general dependence upon the distribution of a number of the observations.

Calculations of areal rainfall using the model have been made over 16 areas within the upper catchment of the River Dee in north Wales. Figure 1 shows the location of these areas, which vary in size from 20 to 112 km^2, and also the locations of the rain-gauges forming the network. This network consists of 60 automatically recording flush-mounted rain-gauges, records from which are processed to a computer-accessible form by the Dee and Clwyd River Authority and the Water Resources Board. The rain-gauges used are flush-mounted modified battery-operated Plessey MM37 tipping-bucket gauges, which incorporate a ¼-inch magnetic-tape event recorder with a time resolution of ¼ hour, events being recorded for each 0·2 mm of rain.

Areal rainfall model. The areal rainfall is obtained by finding the mean value of grid-point estimates within the area, with grid-point spacing in the examples presented here of 1 km and point estimates obtained by

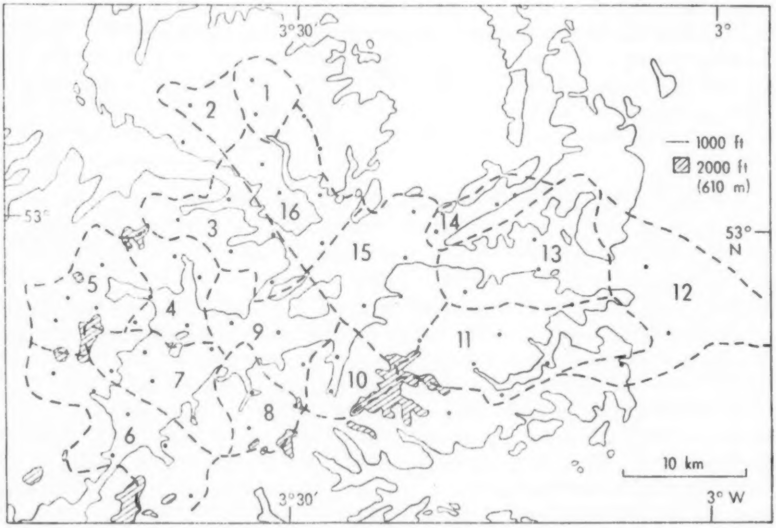

FIGURE 1—SUB-CATCHMENT OF THE RIVER DEE (NORTH WALES) AND RAIN-GAUGE LOCATIONS

applying a mathematical model to a number of nearby gauge observations. This model consists of fitting a linear surface to a grid point with inverse distance-squared weighting applied to the observations. The surface chosen is the one for which the expression $\frac{r}{d} = \frac{ax}{d} + \frac{by}{d} + \frac{c}{d}$, applied to a number of gauge values, has the least-squares solution such that

$$\sum_{i=1}^{N} \frac{1}{d_i^2} \left(r_i - (ax_i + by_i + c)\right)^2 = \text{minimum}$$

where

d	is the distance of the rain-gauge from the grid point,
x and y	are rectangular displacements of the rain-gauge from the grid point,
r	is rainfall value at the gauge, and
a, b, c	are coefficients.

Mathematical solution. For each of the N chosen observations one can write

$$\frac{r_i}{d_i} = \frac{ax_i}{d_i} + \frac{by_i}{d_i} + \frac{c}{d_i}$$

where $i = 1$ to N.

Written in matrix form the N equations become $\mathbf{R} = \mathbf{X}\,\mathbf{A}$

where **R** is the $N \times 1$ matrix with elements r_i/d_i,
X is the $N \times 3$ matrix of displacements with elements,

$$\begin{matrix} \frac{x_1}{d_1} & \frac{y_1}{d_1} & \frac{1}{d_1} \\ \frac{x_2}{d_2} & \frac{y_2}{d_2} & \frac{1}{d_2} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \frac{x_N}{d_N} & \frac{y_N}{d_N} & \frac{1}{d_N} \end{matrix}$$

and **A** is the 3×1 matrix of coefficients with elements *a, b* and *c*. We require the least-squares solution of $\mathbf{R} = \mathbf{X}\,\mathbf{A}$ for the unknown coefficients **A**. The solution is a standard one and can be found in many texts.[8]

$$\mathbf{X}'\,\mathbf{R} = \mathbf{X}'\,\mathbf{X}\,\mathbf{A}, \text{ where } \mathbf{X}' \text{ is the transpose of } \mathbf{X}$$

so that $(\mathbf{X}'\mathbf{X})^{-1}\,\mathbf{X}'\,\mathbf{R} = \mathbf{A}$, where $(\mathbf{X}'\mathbf{X})^{-1}$ is the inverse of $(\mathbf{X}'\mathbf{X})$.
All the left-hand side of this equation is known and coefficients *a, b, c* can be obtained. If the grid point being considered is taken as the origin of the *x, y* system of co-ordinates, i.e. $x = y = 0$, the minimum solution gives an expected rainfall value of *c* at the grid point.

Computer solution. The main steps in the computer solution are to :

(a) select a grid point from a regular array and make this the origin of the rectangular co-ordinates;
(b) select the nearest six suitable observations to the grid point (the nearest six will not necessarily be the best selection and this is discussed further below);
(c) apply the matrix solution to the six observations and take for *r* the resulting value of the coefficient *c*;
(d) take each grid point in turn;
(e) calculate areal rainfall by obtaining the mean of the values for the grid points within the area.

The stability of the solution near to and within the area of the observations is normally high and the most likely cause of instability in the solution is when displacements from a straight line are small compared with the distance of the grid point from it. Such situations result in a very low value of the determinant $\mathbf{X}'\,\mathbf{X}$ and this can be used to ascertain the approach of instability which may then be avoided by changing the choice of gauges used until an acceptable determinant is found. The value of the determinant at which the selection of gauges is rejected may be used to control the distance interpolation is allowed away from the area covered by the observations. For the present purpose interpolation is allowed to the limit of a 60 by 40 array in order that isohyets may be drawn by a computer method which requires a complete rectangular matrix of values.

On occasions an observation will lie very close to a grid point resulting in a small value of one of the distances used in the solution, which in turn can lead to a failure of the model. To prevent this situation the distances are tested and if one falls below some set limit, in this case 0·01 of a grid space, the nearest observation is used as the grid-point value. Interpolation into areas of no rainfall often leads to negative values which are then set to zero.

The present model uses six gauge values to obtain its solution although it could be solved with a minimum of three observations. It has been found that six values give the most acceptable results producing a pattern similar, in most cases, to what an analyst might produce by hand, a number less than six often leads to discontinuities and irregularities in the fields, whilst a number more than six tends to produce too much smoothing as well as consuming more computer time.

Results from the model. An example of a rainfall field produced by the model is shown in Figure 2 where the rain-gauge values used are given and the isohyets drawn by a computer method which relies solely upon the computed grid-point values (not shown). This type of output allows the computer solution to be checked subjectively, as if the isohyets are consistent with the rain-gauge values it can be assumed that the interpolated grid-point values are realistic. Interpolations for a field outside the region of the gauge measurements show some discontinuities such as that marked A near bottom centre of Figure 2. These discontinuities are the result of interpolations being carried out at some distance from the observations and are usually in a location where adjacent grid points are calculated from a different selection of the remote gauges. Within the region covered by the gauges the computed fields are similar to those which an analyst might obtain by hand from a knowledge of the observations alone.

In order to make some comparisons between the value derived from the method used here and the value of areal rainfall which one would accept as the correct one, it is necessary to derive the latter. The best field one can obtain by using the gauges is that which is subjectively drawn by the hand of an analyst but even here, as interpolation is necessary, a degree of uncertainty exists. The hand estimates of areal rainfall were obtained by superimposing a matrix of grid points on the hand-drawn charts and finding the mean of the grid-point values in each of the areas. Not all of the 60 gauges were available for each field examined and the data were so sparse in a few areas that an estimate was unreliable.

Table I shows five cases where a comparison is drawn between the results of the model and the hand computations. Except in a few instances the difference between the two values is small and within the uncertainties inherent in any interpolation method. The two main causes of significant differences are :

(a) the difficulty of defining both hand and computer fields owing to lack of suitable observations particularly when a field is not uniform, e.g. area 1 in Figure 2,

and

(b) high rainfall gradients such that the position of the grid relative to the field is critical. This is the case in area 4 of Figure 2 where a strong gradient exists over the south-eastern part of the area and small changes in the position of the grids of both hand and automatic methods can produce areal estimates differing by as much as the discrepancy in the comparison made in Table I.

Both the above effects are accentuated by having areas containing few observations and a grid which is coarse relative to the size of the areas. This is shown by the measures used to describe the differences between hand and

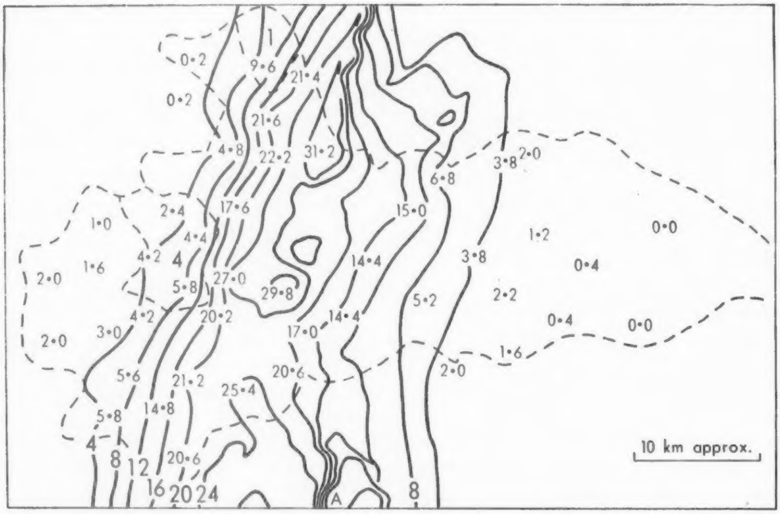

FIGURE 2—RAINFALL CHART FOR 3 HOURS STARTING AT 0545 GMT, 1 AUGUST 1972

Rainfall values are in millimetres and in each case the decimal point indicates the position of the rain-gauge; isohyets are at intervals of 4 millimetres.

TABLE I—COMPARISON BETWEEN HAND AND MODEL COMPUTATIONS OF AREAL RAINFALL

	31 July 1972 1245–1345 GMT			31 July 1972 1345–1445 GMT			1 August 1972 0245–0545 GMT			1 August 1972 0545–0845 GMT			1 August 1972 0845–1145 GMT		
	X	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*
Area															
1	0·3	0·1	0·2	0·0	0·0	0·0	22·7	23·7	1·0	12·1	13·6	1·5	2·4	3·1	0·7
2	0·6	0·3	0·3	0·0	0·0	0·0	18·6	20·4	1·8	4·0	6·0	2·0	0·3	0·8	0·5
3	1·6	1·7	0·1	1·3	1·6	0·3	14·6	12·9	1·7	14·6	15·1	0·5	2·3	2·5	0·2
4	1·5	1·9	0·4	4·0	3·3	0·7	17·9	16·7	1·2	5·1	7·7	2·6	0·1	0·4	0·3
5	0·2	0·5	0·3	2·1	2·4	0·3	15·2	16·7	1·5	1·9	1·9	0·0	0·0	0·0	0·0
6	0·8	0·6	0·2	0·6	0·7	0·1	13·2	12·3	0·9	9·6	10·3	0·7	0·8	1·4	0·6
7	0·4	0·5	0·1	1·8	2·3	0·5	10 0	9·3	0·7	13·2	13·4	0·2	1·2	1·8	0·6
8	0·4	0·6	0·2	2·2	2·5	0·3	2·5	2·1	0·4	24·4	22·0	2·4	8·4	9·1	0·7
9	2·0	1·6	0·4	4·8	5·7	0·9	2·9	2·7	0·2	23·8	22·2	1·6	8·0	7·4	0·6
10	1·4	1·5	0·1	6·4	6·1	0·3	0·5	0·5	0·0	12·3	11·3	1·0	6·4	7·2	0·8
11	1·9	1·9	0·0	3·4	2·8	0·6	0·1	0·1	0·0	2·0	1·4	0·6	4·5	3·3	1·2
12	—	—	—	—	—	—	0·0	0·0	0·0	0·0	0·1	0·1	0·2	0·2	0·0
13	1·0	1·1	0·1	2·0	1·6	0·4	0·1	0·1	0·0	2·0	1·6	0·4	5·2	4·5	0·7
14	0·1	0·3	0·2	1·1	1·3	0·2	0·3	0·2	0·1	4·2	3·2	1·0	8·7	7·8	0·9
15	2·5	2·1	0·4	4·3	4·3	0·0	1·0	1·0	0·0	15·2	11·5	3·7	7·2	7·5	0·3
16	1·8	1·5	0·3	0·7	0·7	0·0	9·0	9·5	0·5	25·0	24·0	1·0	5·6	7·2	1·6
Total	16·5	16·2	3·3	34·7	35·3	4·6	128·6	128·2	10·0	169·4	165·3	19·3	61·3	64·2	9·7
Mean	1·10	1·08	0·22	2·31	2·35	0·31	8·04	8·01	0·63	10·59	10·33	1·21	3·83	4·01	0·61
$\frac{\Sigma Z}{\Sigma X} \times 100\%$		20			13			8			11			16	
$\frac{\lvert \Sigma X - \Sigma Y \rvert}{\Sigma X} \times 100\%$		2			2			<1			2			5	

X = Areal rainfall in millimetres by hand method.
Y = Areal rainfall in millimetres from model.
Z = $X-Y$ modulus of difference in millimetres.
$\frac{\Sigma Z}{\Sigma X} \times 100$ = Percentage error in areal rainfall with areas treated individually.
$\frac{\lvert \Sigma X - \Sigma Y \rvert}{\Sigma X} \times 100$ = Percentage error in overall estimate for the areas treated approximately as one large area.

model computations and given in Table I. The indicator used to describe the size of the differences in individual areas (percentage of sum of differences to total of hand estimates) gives values of 8 to 20 per cent with a mean of 14 per cent for the 5 cases, whilst when all 16 areas are combined into one large area the differences are 5 per cent or less. The combination is not truly a measure of areal rainfall over the total area as all the sub-catchments are not of equal size; nevertheless the comparison of the simple totals is valid enough to make the above point.

Use of a background field. Consideration was given to using a background field in an attempt to improve the interpolation technique; one possibility is the topographic field. However almost all storms produce rainfall totals which, although greatly influenced by the mountains, are not consistently correlated to the ground features on the space and time scale of interest here. For example in Figure 3 is shown a rainfall field, drawn by hand, over a six-hour period in a showery westerly situation on 12 November 1972. It would clearly be unwise to use altitude as a background in such a case, and in consequence this method was rejected.

A second possible background field for use in short durations, i.e. an hour, is the total storm accumulation. Kelway and Herbert[9] used a technique of taking percentage of storm amount at each gauge in order to produce fields of this element and although the method when applied to fields over the Dee Catchment did show the general movement of the main rain features quite well, no noticeable improvement in the interpolation resulted. In fact some short-duration fields show few of the features of the total storm

FIGURE 3—RAINFALL IN MILLIMETRES BETWEEN 0130 AND 0730 GMT, 12 NOVEMBER 1972

In each case the position of the rain-gauge is indicated by the decimal point.

amount and the use of such a background on these occasions could degrade the interpolation.

Conclusion. From a scattered array of observations the model allows automatic interpolation of realistic rainfall fields from which areal rainfalls can be calculated over an area of any shape with sufficient accuracy to permit them to be used in routine analyses. For five cases a mean error of 14 per cent was obtained between the model and hand estimates over areas which were relatively small compared with the grid spacing. The model allows isohyets to be drawn by a computer method which permits subjective surveillance of the interpolation.

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METEOROLOGICAL CONTRIBUTIONS TO OPERATIONAL HYDROLOGICAL FORECASTING IN THE UNITED KINGDOM

By A. BLEASDALE

Summary. Meteorologists have an important part to play in aiding hydrological forecasting. The associated problems and the stage now reached in solving them within the natural and organizational setting in the United Kingdom are outlined. In this country, in present practice, hydrological forecasting means, predominantly, forecasting rainfall-produced river floods and issuing appropriate warnings. But there are other forecasting problems within the hydrological field, for some of which interesting and promising developments are taking place. These are also touched on.

Introduction. This note was originally written to suggest material for possible inclusion in a joint paper, with hydrologists as co-authors, on operational hydrological forecasting systems in the United Kingdom. The joint paper was presented at a WMO–Unesco meeting on hydrological problems held at Berne in August 1973. The material was intended to be very freely used and rearranged amongst the hydrological contributions, a course which was in fact taken. Moreover the meeting at Berne was organized on a small scale, primarily to stimulate free discussion, not necessarily with the follow-up of international publication of the full proceedings. The note can stand on its own, though it might well have taken another form, with some differences in wording, given a more independent origin.

As the State Weather Service in the U.K., the Meteorological Office includes among its functions the provision of meteorological services to the community in general. Many regular recurrent needs are met by the frequent issue of weather reports and forecasts through public information channels. It is known that this continually up-dated form of communication can also be used, at least to initiate a preliminary alert based on a specified meteorological threshold, by organizations which have, beyond these thresholds, their own specialized requirements. With or without this tentative alert, special needs are met by arrangements which, in most cases, have been built up gradually over the years, and from time to time undergo significant development. Improvements in this sense often arise as the direct result of an extreme or otherwise unusual weather or weather-influenced event which has presented a problem: great difficulties of some kind, serious loss or damage, or even disaster.

Important examples of special needs are warnings of disruptive weather effects on transport, in particular snow, ice or fog hazards lowering the safety and efficiency of road and rail services, and dangers from strong winds to traffic crossing vulnerable bridges or traversing other elevated and exposed sections of route (to say nothing of shipping and aviation).

Each special need offers its own peculiar problems to the meteorologist, not only because of the intrinsic difficulty of weather forecasting in general, and the very small changes in some meteorological elements which can rapidly transform a safe situation into a dangerous one (slow thawing or refreezing; dispersal or thickening of slight fog), but also because some variations on hazardous conditions cannot be foreseen, or at least in practice have not been foreseen, until they have occurred at least once and have enforced study.

In the past fifteen years it has become increasingly recognized in the U.K. that one of the most important of the specialized meteorological services is the contribution which can be offered to hydrological forecasting. In some of its branches the latter has itself, during the same period, become established, and is now being maintained and developed, on a sound operational basis, so that in this field the totally unforeseen should become a much rarer phenomenon, and there is more opportunity for the most damaging effects of the foreseen to be prepared for and mitigated.

One stimulus towards the new outlook came from the Lynmouth flood disaster of August 1952,[1] though the greatest outburst of productive activity in developing flood-warning systems did not follow until interest was renewed by the notable flood year of 1960,[2] within an organizational setting which was then becoming more favourable. It was again reinforced by the outstanding rainfall-flood events of 1968,[3] but there had also been a less concentrated train of incidents to maintain a useful degree of steady progress.

It is relevant to note that operational hydrological forecasting in the U.K. is very largely concerned with rainfall-produced river floods, and that the North Sea surge of late January 1953,[4,5] which caused disastrous tidal flooding from north of the Humber to south of the Thames, very probably diminished the still lively interest in the Lynmouth event, thereby delaying for some years any concentration of effort on flood-warning schemes for rivers. These two floods remain as yet the latest in the U.K. in which loss of life has occurred on a substantial scale, and the later (1953) far surpassed the earlier (1952) in this respect.

Whilst the tidal surge type of flooding is not hydrological in the usually accepted sense of the term, the Storm Tide Warning Service which has been developed, following 1953, is dealt with here (see page 306) for two reasons: there are possibilities that a tidal surge could coincide with and seriously aggravate the damage and difficulties of a rainfall-river flood, and river engineers in the U.K. are rightly very concerned about this; and secondly, this Service is one in which the U.K. is collaborating with other European countries bordering the North Sea.

There are of course other forms of hydrological forecasting with their own special problems for meteorologists, which will be touched on briefly later. Among the most important in the U.K. are :

(a) snowmelt floods;
(b) short- and medium-term water resources management (the long-term requires planning rather than forecasting).

The meteorological contribution to river-flood forecasting presents problems in three different categories, with varying degrees of difficulty in finding operationally adequate solutions :

(a) a continuous watch on flood susceptibility in river basins throughout the country, to judge when the season arrives to be specially alert for any forecast of substantial amounts of rain;
(b) the general forecasting of heavy or more moderate but prolonged rainfall, with as much information as possible on the likely severity and duration, and the areas likely to be affected;
(c) the more detailed and precise forecasting of intense falls of rain likely to affect small river basins subject to flash floods, and urban storm-water drainage systems.

The arrangements which have been made to attempt to cope with these problems and difficulties illustrate a very important factor towards achieving success: the co-ordination of activities on national, regional and local levels. For the assessment of flood susceptibility the Meteorological Office has continuously developed, since the autumn of 1962, a national service for estimating and mapping soil moisture deficits over the whole of Britain. Bulletins, with maps and tabular summaries showing the (estimated) state of the ground in this sense, are issued at approximately fortnightly intervals throughout the year, except for those months (slightly variable but mainly winter and early spring) when it is estimated that, with negligible exceptions, soils everywhere are at field capacity, and virtually all rain which falls can be assumed to be 100 per cent effective rainfall. In the present context the most interesting period is usually the autumn, when the area of zero soil moisture deficit spreads progressively over the whole country, and one area after another approaches its maximum susceptibility to any threat of flood-producing rainfall. An example of a pair of successive autumn–winter soil moisture deficit maps is given in Figures 1 and 2. Through the development of the computer model on which the preparation of these bulletins is based (they were originally introduced with entirely manual procedures), the service will shortly be extended and improved to provide regular countrywide assessments of potential evaporation, actual evaporation, soil moisture deficits and effective rainfall. To derive maximum benefit from the national service, users (who include many with interests other than the flood-alert application) should if possible employ local checks on the validity of the rather generalized

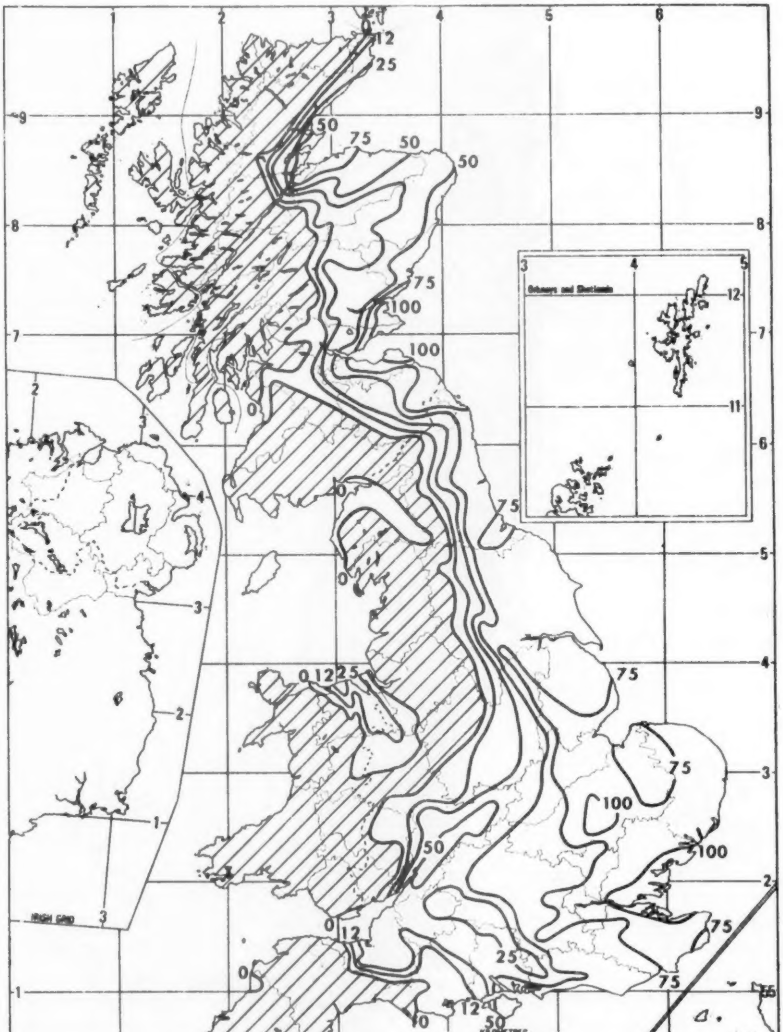

FIGURE 1—ESTIMATED SOIL MOISTURE DEFICIT AT 09 GMT, 29 NOVEMBER 1972

Areas with no soil moisture deficit are shaded. Remaining areas are bounded by lines representing 0, 12, 25, 50, 75 and 100 millimetres.

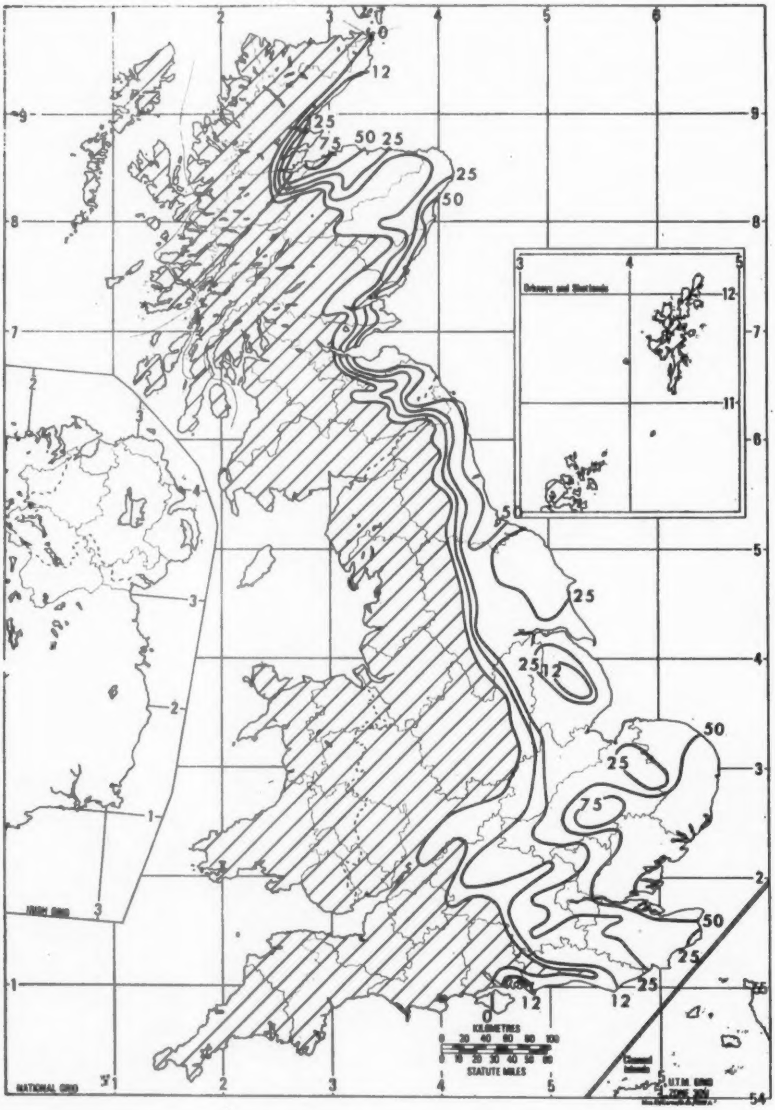

FIGURE 2—ESTIMATED SOIL MOISTURE DEFICIT AT 09 GMT, 13 DECEMBER 1972
Areas with no soil moisture deficit are shaded. Remaining areas are bounded by lines representing 0, 12, 25, 50, 75 and 100 millimetres.

small-scale maps. One such check, used with striking success over a large area in the south-west during the autumn of 1972, is to observe the date on which field drains begin to run, which should be with the first fall of rain sufficient to bring soil moisture deficits back to zero, with at least a little extra. Coincidence of estimates and observations has been achieved within a day or two, though it must also be admitted that there are still occasional anomalies of several days which require investigation in order to improve the data input or the model, whichever seems to be at fault. Reference No. 6 indicates the means to obtain fuller information about this service.

The quantitative forecasting of rainfall is still a major problem, which is being tackled at the national level by the development of the 10-level atmospheric model[7] now being run twice a day as an operational routine on the Meteorological Office IBM 360/195 installed in December 1971.[8] For the flood-forecasting application, however, the Meteorological Office has always encouraged, whatever the mode of forecasting at Headquarters, regional and local interpretation, at Meteorological Office stations manned by trained forecasters throughout the country, of the central guidance on current meteorological developments. The present position is that more than 20 weather centres and other offices have established direct communications with 28 of the 29 river authorities covering the whole of England and Wales, on matters relevant to flood warnings. Example: the office at Gloucester issued to the Bristol Avon River Authority at 20 GMT on 14 January 1973 the forecast :

> 'Continuous rainfall over Cornwall is expected to spread over your area this evening and tonight, persisting throughout the night; 12·5 mm (0·5 inch) or more of rain is expected to occur in 6 hours locally.'

From the soil moisture bulletins already issued it was known that zero deficit had been reached in this area before mid December (Figure 2) and therefore that any substantial rainfall would produce high flows in the trunk river flowing through Bath and Bristol, perhaps also in smaller towns vulnerably situated on the Bristol Avon or its tributaries. At such a point it is for the hydrologists to take over, with any actions which they consider necessary or desirable, including attention to actual measurements of rainfall, for which immediate transmission to an operational centre will have been pre-arranged, in order to check the forecast. In this instance, the forecast proved correct, though a check (perhaps not exhaustive) showed that only two stations strictly within the river basin, on relatively high ground, measured rainfall amounts above the specified threshold; some on lower ground failed to reach half the amount. An area of heavier rain in fact passed slightly to the south of the Bristol Avon basin, and the situation illustrates one of the special difficulties for meteorologists in contributing to flood-warning services, particularly for the smaller rivers: namely the accurate specification of which, amongst a group of neighbouring basins, will be most seriously affected. Especially when the heaviest rain falls on high ground which is a drainage divide, a slight shift in the rain area, from that forecast, could transfer the most serious flood risk from one area to another. A very good account of rainfall forecasting for three river authorities has been given by Holgate.[9]

The difficulty referred to above is greatly enhanced with the problem of forecasting intense short-period rainfall, usually of an irregular thundery type, which may produce flash floods in the smallest natural drainage basins, and

serious trouble for urban storm-water disposal. In these conditions, too, quite moderate departures of intensity and duration, from those suggested by an attempted forecast, can sometimes make all the difference between a mere nuisance and real trouble if not disaster; whilst the possible benefits from a substantial soil moisture deficit, which may be experienced with more moderate and prolonged rain in the larger river basins, can be negligible for the most intense short-period bursts, either because any deficit may be nullified during the first few minutes, or because infiltration rates cannot match the rainfall rates (not to mention completely impermeable surfaces). The problems have not yet been solved, but there is a current upsurge of interest in the U.K., arising in a number of ways, and stimulating activities which are likely to converge productively within the next few years :

(a) Following the very exceptional rainfall and flooding of 10 July 1968,[3] it was remarked by some of those concerned, including the Engineer of the Bristol Avon River Authority, that the larger rivers behaved at any rate predictably, whilst much of the serious damage, including the destruction of bridges (at least one of them centuries-old) occurred on the small tributaries. Several similar incidents in small stream basins have happened in recent years to keep interest alive.

(b) The papers prepared for a research colloquium at Bristol University, in April 1973, have drawn attention to the data needs and further investigations required to cover drainage and flood problems in large and growing urban areas.[10] Relevant investigations have already begun or are being planned, but the discussions at the colloquium are likely to stimulate others by bringing out additional requirements not previously foreseen.

(c) Outstanding amongst current investigations is the Dee Weather Radar Project.[11] Started in order to investigate the usefulness of rainfall-radar in a major river-regulation scheme, the Project is also providing data which are very useful for the study of the movement and development of rainfall systems, including the irregular thundery distributions which give so much trouble to the hydrologically-oriented rainfall forecaster.

(d) It may also be mentioned that two flood studies teams, of meteorologists and hydrologists, completed in 1973 a major three-year programme of work, results shortly to be published, which though directed primarily to the hydrological design and not the forecasting problem, assembled much useful background information for the latter.

Even with radar, it is to be doubted whether the flash-flood problem will ever be completely solved, in the sense of prediction, sufficiently far in advance, of the precise small area within which the heaviest deluge in an exceptional fall will occur, and of being able to take full protective measures in time. But there are prospects of much better results than could be achieved with any practicable density of conventional rain-gauges, or any foreseeable refinement of meteorological forecasting techniques. The very fine scale required for intense rainfall forecasting over small drainage areas, goes so very much below the dimensions of any numerical-model grid which can as yet be envisaged, even for the most advanced atmospheric model and the largest and most powerful computers.

The study of snowmelt floods in the U.K. has distinctive problems. A really severe winter affecting most or all of the country does not occur very often. The last was 1962–63, the two before that 1946–47 and 1939–40. In 1947 there were large-scale catastrophic floods, especially in the Fens of East Anglia, in some other parts of south and south-east England, and in several parts of Yorkshire, notably a large area in the plain of York, on both sides of the Ouse from the confluence with the Wharfe to the confluence with the Aire.[12,13] Snow had accumulated for about two months when, towards mid March, a very mild and vigorous south-westerly airstream suddenly caused a very rapid thaw, which was also accompanied by frequent rain. Few people, if any, had realized that disaster might occur on such a great scale. Snow accumulation in 1962–63 was appreciably smaller but a flood danger existed. Special efforts were made by the Meteorological Office to collect snow-lying data and assess the degree of the potential flood risk; in a few places, notably in north-east England, where floods did occur, the assessments proved to be fairly good. But in general the thaw came slowly (slight thaw by day, refreezing at night) over a rather prolonged period, and over most of the country there were no serious floods. There are few opportunities to study severe winters and improve snowmelt forecasting techniques. A much more frequent winter sequence in most parts of the U.K. produces a number of short-lived snow periods, each followed by a milder spell in which there may be floods with a substantial snowmelt contribution. The assessment of the danger is then more difficult. Very often there is not much time to survey the temporary snow fields, which may be largely in hilly and thinly populated areas. A major problem is simply organizational. If snow surveys of any kind are to be carried out, the teams responsible must have other work to do, as otherwise, in some winters, they would literally do nothing at all. Yet the nature of the other work would have to be such that all activity could be suspended completely at very short notice, for any period that might be necessary, whether brief or prolonged. Some progress is, however, being made, both in snow-data collection, when opportunity occurs, and in adapting to British conditions Canadian work on snowmelt computations.[14] Comprehensive instructions have been issued to those Meteorological Office stations maintaining contact with river authorities; the aim is that they should test the method as often as possible, first, as an aid to useful qualitative forecasting; next, on a trial basis and to begin with entirely within the Meteorological Office, until consistently good results can be achieved, as a means of introducing a quantitative method of forecasting snowmelt.

The meteorological contribution to short- and medium-term water resources management is for the most part not yet in a very advanced stage. Continuous efforts are being made to improve short- and medium-term weather forecasting in general, not without some success, but the quantitative rainfall element in these forecasts is certainly amongst the most difficult, perhaps the most difficult of all. Until the forecasts can be improved in quantitative rainfall terms, greatest hopes for a substantial measure of success in aiding water resources management are probably to be found in current developments in river-flow regulation. In so far as these are concerned solely with surface water the Dee investigation[11] is the most advanced in the U.K. In some other areas, including the Thames valley, recent advances have been made in studying the techniques of augmenting river flow, during periods of

rainfall deficiency, by pumping from groundwater into the surface channels. For this operation, advances in short- and medium-term quantitative rainfall forecasting would undoubtedly help, but use can already be made, and has been made, of the estimated soil moisture deficit service (page 300 and Reference No. 6) in order to obtain estimates of the natural recharge of the pumped aquifer when sufficient rain has brought the soil moisture deficit to zero. It is interesting to observe that during the period when this note was being drafted (spring 1973) there was a nine-month rainfall deficiency (July to March) affecting most of the U.K., but to a specially serious degree parts of eastern England and Scotland. Deficiencies reaching or exceeding 50 per cent of the nine-month average had accumulated in some areas. For England and Wales as a whole, the deficiency was the most severe for this particular sequence of nine months, as far as can be estimated, since 1749–50. Meanwhile, soil moisture deficits which had accumulated during the summer and early autumn of 1972 had not been eliminated during the winter and were beginning to increase again (rapid increase in rates of evaporation, beginning to match even average rainfall). The subsequent rainfall, during a moderately wet two months, April and May, was of course far short of being fully effective as a contribution to available water resources, the more so in those areas with soil moisture deficits very much above the average for the time of the year. In places, even by the end of March, the excess of the deficits beyond the average amounted to 40 mm or more. The deficiency estimated from analysis of rainfall in isolation was to the same degree enhanced in the water resources sense. There was already a possibility of rudimentary hydrological forecasting, which in a limited way was put into action operationally: given certain threshold values of rainfall minus evaporation in the succeeding weeks and months, the probabilities of which could be estimated empirically from past data, it was a practicable exercise to estimate (and subsequently check) the delays, having the same probabilities, which would occur before any substantial amounts of rain could become effective either as surface water and river flow, or as contributions to groundwater. This type of exercise was in fact the basis and object of the original paper by Grindley,[15] reporting work carried out in arrear for the 1959 drought in the U.K., which led eventually to the present soil moisture deficit service.

The Storm Tide Warning Service came into being after a committee of inquiry[5] had reported its findings on the east coast floods of 1953, and made recommendations on many matters, including the future of the warning system. As at present organized the Warning Service is housed within the Meteorological Office Headquarters at Bracknell in close association with the Central Forecasting Office there, with staff provided by the Hydrographer, Ministry of Defence (Navy), whilst it is administered by the Ministry of Agriculture, Fisheries and Food, Land Drainage Division (MAFF LDD), which has responsibilities at national level covering all forms of flooding. The task of the Service is essentially to keep a continuous watch on variations from the astronomically predicted tides, and maintain close liaison with the meteorological forecasters, in order to observe and forecast the development of any significant positive variation or surge which, if associated with the predicted high tide, could lead to dangerously high levels along vulnerable coasts. The number of tide gauges used, at northern and east coast sites, has been increased to eight (see Figure 3) and the readings of these gauges are

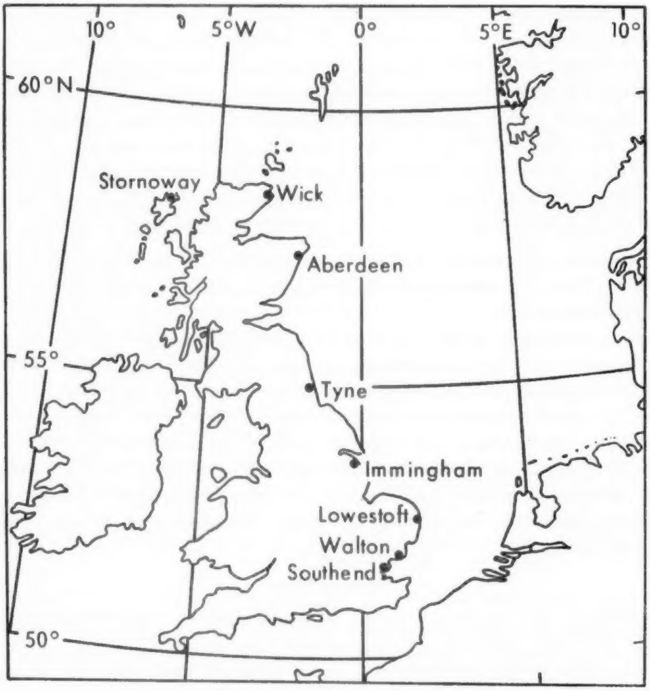

FIGURE 3—LOCATION OF TIDE GAUGES

transmitted continuously to Bracknell where they are visibly recorded on cylindrical drum charts, which already carry the curves representing the cycle of the astronomical tide. The operational season lasts from the spring tides of late August or early September to the end of April, as there is little danger in the meteorologically quieter summer months. During alerts MAFF LDD is kept fully informed and warnings are issued as necessary to the police in the areas which may be endangered, who in turn pass them on to the river authorities responsible for coastal protection. A few other authorities are also involved notably the Port of London Authority, with responsibilities extending along the entire tidal length of the river Thames and its estuary. The number of warnings issued varies greatly from season to season, according to the dominant weather types, but the following are approximate averages per season :

alerts	100
alerts subsequently cancelled	75
alerts continued as 'alert confirmed'	20
alerts leading to danger messages	5

(The alerts or danger messages are issued as necessary to any of five divisions extending from Berwick-on-Tweed to the Straits of Dover, so that more detail and more accuracy can be attempted than with a single forecast of tide levels along the whole stretch of coast.) In addition to the service for the east coast of Britain, the Storm Tide Warning Service provides information twice a

day to the Netherlands (Koninklijk Nederlands Meteorologisch Instituut) and the Federal Republic of Germany (Deutsches Hydrographisches Institut). Hourly readings of the tide gauges at Aberdeen, Immingham and Lowestoft are supplied for 0400 to 0900 at 09 GMT and for 1000 to 1500 at 15 GMT. If the situation is such that a night watch is required additional messages are sent at night. The times of high and low water at Aberdeen and Immingham are also provided. In addition Denmark has shown interest and has been provided with information about the nature and organization of the Service. Papers on the scientific investigation of surges have been published.[16]

Conclusion. The current stage of development in hydrological forecasting in the U.K., and of meteorological contributions in this field, represent a very great advance on the situation about 15 years ago, though some of the developments referred to had in fact been initiated even earlier. The period selected may be viewed in retrospect as one of almost continuous activity in this field, triggered off by impressive natural events, some of which were legitimately termed disastrous, and boosted at intervals by other such events. The fact that the activity has been so fruitful, and should be even more so in the future, owes much to the development of appropriate organizational forms at national, regional and local levels, and to energetic and harmonious collaboration between organizations which, working in isolation, would be much less effective.

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REVIEWS

Times of feast, times of famine: (a history of climate since the year 1000), by Emmanuel Le Roy Ladurie (translated by Barbara Bray). 240 mm × 180 mm, pp. xvi + 428, *illus.*, George Allen & Unwin Ltd, Ruskin House, Museum Street, London, 1972. Price: £7·35.

The author of this book is professor of history at the University of Paris. He is to be congratulated on writing a fascinating, readable and very convincing book on the detailed history of climate since the Middle Ages with some, naturally less definite, conclusions concerning climate before then. He marshals his facts and sources of information in a very logical and convincing way which leaves little room for doubt that the story he unfolds is the correct one, at least for the last 400–500 years. Although concerned mainly with continental Europe, the facts he produces indicate that it is probable that the changes of climate he recounts occurred at about the same time in places as far afield as Arizona, Alaska, Iceland and Norway.

Most of the argument is based on careful assessment of the results of recent work on dendrochronology, the dates of European wine harvesting and the history of glaciers, mainly in the Alps. Professor Ladurie, however, takes nothing for granted; in almost every matter he has consulted the original records including a host of surviving documents many of which he has himself unearthed.

He gives an excellent account of the methods of dendrochronology and points out that the interpretation of tree ring data is not always easy. Different species react to different climatic effects; in the near deserts of Arizona for instance a wide ring means a wetter than usual growing season whereas in the Arctic, tree growth is sensitive mainly to summer temperature. In other parts of the world tree growth may reflect both temperature and rainfall to varying degrees and in different seasons. It is first necessary to correlate recent rings with known meteorological data before trying to establish past meteorological régimes from tree remains dug up from peat bogs, etc. Using these methods on the Bristlecone pine, Fritts in Arizona has recognized 9 climatic classes for each season and as a result each season for the last 7000+ years has been classified.

He is equally thorough in his discussion of wine harvests, noting particularly that it is not so much the latitude to which grapes can be grown that reflects the climate but rather the date on which the grapes are ready for gathering. Grape growing may be abandoned in certain areas for economic reasons but the date of ripening in a particular region is highly correlated with temperature and sunshine over the period May to September.

It is, however, in his discussion of Alpine glacier changes that Professor Ladurie comes into his own. The wealth of evidence produced from contemporary documents, engravings, etc. leaves no room for doubt that, after a period of relative glacier recession before about 1550, the glaciers advanced so far that by 1600 they had reached a stage hitherto quite unknown. With minor oscillations this stage lasted until about 1850 since when up to about 1955 at least, an even more noticeable recession has taken place. These changes are correctly attributed more to changes of summer temperature, rainfall and cloudiness than to winter temperatures. It is a pity, however, that Professor Ladurie does not give more attention to the worldwide cooling

trend which has taken place since about 1955, of which he is clearly aware but on which he does not comment as regards the glaciers.

The book is also valuable in collecting together many important references and quoting much useful data. Notable in this respect are the wine harvest dates produced by Müller for Germany for every year since 1453 and the Aspen diagrams, pooling climatic information from all sources for the 11th and 16th centuries. The reviewer was also unaware of the monthly mean temperature series available since 1773 for Annecy (France). Another interesting point to the meteorologist is that these early records indicate a high frequency of sequences of years (from about 4 to 12 or 15) of similar weather types (wet summers, cold winters, etc.); the biennial oscillation is much less apparent.

One could criticize some aspects of the book, the paper is of rather poor quality which results in some of the diagrams being difficult to read, the appendices are poorly laid out and difficult to follow while some of the references to the Aspen diagrams in the text are incorrect. Also there is no Figure 31 although one is referred to in the text. The translation is excellent throughout; the only error I noted was 'meridian' for 'meridional' on several occasions in the last chapter.

Altogether I thoroughly recommend this book to anyone interested or involved in the study of the history of climate although at £7·35 I think not many will buy a personal copy!

R. A. S. RATCLIFFE

Weather forecasting for agriculture and industry, edited by J. A. Taylor. 215 mm × 155 mm, pp. xix + 250, *illus.*, David & Charles (Publishers) Ltd, South Devon House, Newton Abbot, Devon, 1972. Price: £5·75.

The arrival of an authoritative book devoted to such important subjects as the value and use of weather forecasts and meteorological services in agriculture and industry, would have been welcome any time in the past decade. In relation to the doubling of inquiries for weather advice given by the U.K. Meteorological Office during this time, and to the fresh problems involving weather-dependent aspects of agriculture and of industry likely to arise as a result of Britain's entry to the E.E.C., the timing of this publication of seventeen papers, presented during the 1971 Symposium of the University College of Wales, Aberystwyth on these subjects, has been a particularly happy one. Each paper has a chapter to itself and was written and delivered at the Symposium by an acknowledged authority on the topic under discussion. So for the most part the writers' findings and proposals can be endorsed with enthusiasm and confidence.

The first eight chapters are concerned with weather and climate forecasting over a wide range of time scales mainly for agricultural purposes. Suggestions for reorganizations of current priorities in our meteorological services recur through the themes developed by these authors, such as the urgent need to improve forecasts of timings of onset and cessation of rainfall in particular districts, and the need to improve the present 30-second coverage of the television weather map which is minimal by its own standards and by several international comparisons. Some writers emphasize the potential value of regular weather forecasts and weather summaries for one week ahead

intended specifically for farmers. A most valuable section (pages 46–49) discusses 'the present state of the art' of forecasting and the agronomic uses of forecasts and goes on to consider the value for horticultural activities in numerous instances of forecasts on the five-day, five-month and five-year time scales. In years to come operational forecasters and scientists responsible for planning and administering national forecast services in many countries can well afford to peruse this book at frequent intervals, with advantage and profit to all concerned.

Weather forecasting for industry is concisely dealt with by Mr R. A. Buchanan in a fascinating chapter where he puts in a strong plea for better two-way communication between meteorologists and industrialists. While he leaves the reader in no doubt that the Meteorological Office has many satisfied customers (like the owner of a chain of both fish restaurants and ice-cream shops), it seems a pity that this section scarcely mentions the actual or possible impact of long-range (monthly) forecasts upon industrialists, and that (apparently) no detailed questionnaire has yet been addressed to industrialists, similar to the questionnaire sent to and answered by farmers and growers as described in Chapter 6 and its Appendix.

Longer-range weather and climate forecasting are treated by Professor H. H. Lamb in Chapter 3 in some detail, including a discussion of changes in temperature and rainfall known to have occurred over Britain through nearly three centuries with instrumental records. The probable increase of about 30 days in the length of the growing season between the periods 1680–1700 and 1920–50, and its subsequent slight decrease, sets the problem of climatic change in perspective for agriculturists and other students of human affairs. While techniques used in the Meteorological Office for monthly forecasts are described in detail, the problems of seasonal forecasting receive no mention and climate forecasting for several years ahead, a subject of such vital interest to agriculturists, is dealt with in a single paragraph. The potential importance of climatic forecasting on the scale of 5 to 10 years or longer is however considered by some of the other authors, notably in connection with the design of new reservoirs (Chapter 4), and in connection with actual and possible changes in land use, either in marginal lands on the threshold of unfavourable climates, or due to political pressures caused by population explosions in some tropical countries, or by social–political changes such as those engendered by Britain joining the E.E.C. with its differences in agricultural techniques between the member states.

Although in the preface it is stated that the use of weather forecasts in agriculture and industry is dealt with in particular relation to Britain, it seems unfortunate that so little attention is paid by the contributors in this book to similar uses of forecasts in other countries, particularly those of the third world. This omission weakens a statement in the foreword that 'the contributions to the present volume . . . represent the essential first steps towards the definition, if not the solution of problems of increasing significance in a hungry world'. The broader treatment by Professor A. N. Duckham of the forecasting of biological consequences and of land use reassessment likely to arise due to meteorological and economic factors in tropical and subtropical regions, provides a welcome exception to this situation.

Two loosely written paragraphs on 'climate' and 'standard weather pattern' on pages 87–89, hardly deserve their inclusion in an otherwise interesting

chapter. Fog on motorways which receives a lengthy mention in the preface, is not discussed again, except in a few words on page 116. Perhaps less surprising is the paucity of references to any recent original work on weather forecasting to be found in the selected bibliography for Chapter 12 on page 231, partly reflecting the present dominance of the computer in this field. However, should even a few of the suggestions in this book be adopted for bringing forecast services more closely in line with consumer requirements, then indeed the cost/benefit ratio on any national scale should be a high one. Such benefits, deriving indirectly from purchasers and readers of this book, whether impelled by official or by amateur interests in this field, should ultimately make a real and lasting contribution to human welfare in many lands.

R. F. M. HAY

NOTES AND NEWS

CLEAR-AIR TURBULENCE

Pilots' reports collected during the Spring (1972) investigation of clear-air turbulence have been stored on magnetic tape. They cover over 750 000 km of track at cruise level and allow the proportion of bumpy flight to be compared with indices calculated on the Bushby–Timpson fine-mesh 10-level model. Two indices are being tried at present; one assesses the rate of reduction of the Richardson number in a fluid element as it moves in a deforming flow, and the other assesses the rate of dissipation of turbulent energy made available by larger-scale deformation.

OBITUARY

It is with regret that we have to record the death of Mr J. M. Smith, Senior Scientific Officer, Met O 12, on 3 June 1973.

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